Study of Bake-hardening behaviour of ultra-low carbon BH 220 steel at different strain rates

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF THE

REQUIREMENTS FOR THE DEGREE OF

Master of Technology

In

Mechanical Engineering
[Specialization: Steel Technology]

Submitted by:

PREM PRAKASH SETH

(212MM2462)

UNDER THE GUDIENCE

of
Prof. A.Basu
&
Dr. H.N. Bar (CSIR-NML, JAMSHEDPUR)

Department of Metallurgical and Materials Engineering
National Institute of Technology
Rourkela

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CERTIFICATE

This is to certify that the thesis entitled, "**Study of Bake-hardening of ultra-low carbon BH 220 steel at different strain rates**", submitted by PREM PRAKASH SETH in partial fulfilment of the requirements for the award of Master of Technology Degree in Mechanical Engineering Department at the National Institute of Technology (specialization: Steel Technology), Rourkela is an authentic work carried out by him under our supervision and guidance.

To the best of our knowledge, the matter embodied in the thesis has not been submitted to any other University/ Institute for the award of any degree or diploma.

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N. I.T Rourkela   Prem Prakash Seth

May, 2014

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ABSTRACT

Automotive process adopts bake hardening technique during the paint baking cycle at elevated temperature for enhanced strength of steel by the diffusion of Carbon atoms to the dislocations along with drying of paint. The present study was intended to investigate the bake-hardening (BH) behaviour of ultra-low carbon (0.0027 wt. % C) BH220 steel with different pre-strain values and to justify the work by dislocation density measurements. The specimen were subject to tensile pre- strain of 2%, 4%, 6% and 8% at room temperature followed by bake hardening at pre- defined temperature of 170˚C for 20 minutes. Specimens with a particular pre-strain and pre-strain with bake hardening were subjected to monotonic tensile load at different strain rates (0.001, 0.1 and 100/s). Dislocation density was estimated by X-ray diffraction technique. The result reveals that in case of quasi static strain rate tests, pre-straining increases the yield strength compared to the as received steel in the range of 20-40% , wheres in case of same pre-strain and bake harding combination it is in the range of 30-60%. Similar increase in ultimate tensile strength and bake hardening response was observed. Similar trend was also observed in case of high strain rate tests. This can be attributed towards pinning of dislocation by bake hardening. In dislocation density study, increase in dislocation density was observed with increase in pre-strain level and as well as in strain rates.

Key Words : Bake hardening , Yield strength , Dislocation density , Strain rate , X-ray diffraction.

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CHAPTER -1: Introduction

CHAPTER -1: INTRODUCTION

1.1 Background

All over the world individuals use automobile on regular schedule to reach their destinations, which also brings the risk of road accidents. Only in the European countries 40,000 people die every year due to automotive accidents. Although it sounds cruel to label human life with a very high money value, this mishaps cost the administrations something around 160 billion Euros [1]. So as to decrease fatalities or damages, and even diminish the dimension of mishaps, auto fabricators, governments and private establishments around the globe are cooperating to discover conceivable answers for this colossal issue. So, the way to go ahead towards this target is to get high strength crash resistance steel but obviously not at the cost of increased weight.

To fulfilment this requirement of the automobile industry, many high strength steels have been developed. These include, TRansformation Induced Plasticity steel (TRIP steel), Interstitial Free steel (IF steel) and IF High Strength steel, Complex Phase (CP) steel, Dual Phase steel (DP steel), Martensitic Steels (MS), Bake Hardening (BH) steel, ultra-low carbon steel and High Strength Low Alloy (HSLA). These steels are having different combination of high strength to weight ratio with good formability along with good combination of strength and ductility.

The parts of the auto body board pass through a paint baking cycle (bake hardening process) that is carried out after all the framing operations are finished. In this paint heating cycle, the painted auto body part is dealt with in an oven to dry and to permit the paint to adhere to the substrate steel of the auto. The paint baking process not only gives the car an aesthetically pleasing look, but also positively influences on the strength of the material used for the car structure. The increment of strength which happens during such paint baking process is known as bake hardening effect.

The bake hardening effect can be influenced by many factors like baking condition, strain rate, pre-strain level etc.; but in a established steel and baking cycle pre-straining is the only possibility to increase the mechanical property of the steel. Pre-strained steel subjected to baking leads to formation of pinned dislocation which in turn increase the strength properties. How such variations obtained by baking can change the properties at different strain rate tests and its internal mechanism are well established. BH 220, a bake harden grade steel has recently being used in automobile industries brings lots of attention in this regard.

1.2 Objective

Objectives of the present study are:

1. Determination of mechanical properties of this material (BH 220 steel) at dent condition (quasi-static strain rate) and compare the behaviour with crash conditions (high strain rate).
2. Understand the deformation mechanisms at different strain rates.
3. Analysis of the stress-strain behaviour and correlation with the microstructure.
4. Assessment of dislocation density of ultra-low carbon BH 220 steel at quasi-static strain rates.
5. Fractographic analysis to understand the deformation behaviour at quasi-static strain rate.
6. Study the effect of pre-strain and bake hardening on the previously mentioned factors.

1.3 Structure of the thesis

This thesis has an organisation of many useful data and fact related to the bake hardening. The structure of the thesis is as below.

Bake hardening is an advanced processing technique to produce low carbon and ultra-low carbon steels, used from automobile in paint baking process in car bodies. The Brief study of mechanism of bake hardening and factors affecting bake hardening behaviour is discussed in Literature Review (chapter 2). The experimental techniques used the present study is discussed in the Experimental (chapter 3). The graphical representation of engineering stress-strain plot at different rates, comparative study of tensile propriety at different pre-strain level with each strain rates, fractographic study and dislocation density measurement are discussed in Results and Discussion (chapter 4). The summary of the main findings and the future work scope is mentioned in Epilogue (chapter 5). References used in this study are listed in the last chapter.

CHAPTER –2: Literature review

2.1 Bake Hardening: A brief review

2.1.1 Introduction

Bake hardening utilises the phenomenon of stain aging to provide an increase in the yield strength of formed auto-motive components. In automotive outer body applications, this strength increment is developed during the relatively low temperature (160 ± 180°C) finishing treatment required to bake the paint coatings, during which interstitial solute atoms migrate to the dislocations produced during pressing. Since it requires no additional process steps, bake hardening does not significantly affect production costs, and can also allow a greater finial strength level to be achieved in higher formability grades with high dent resistant .

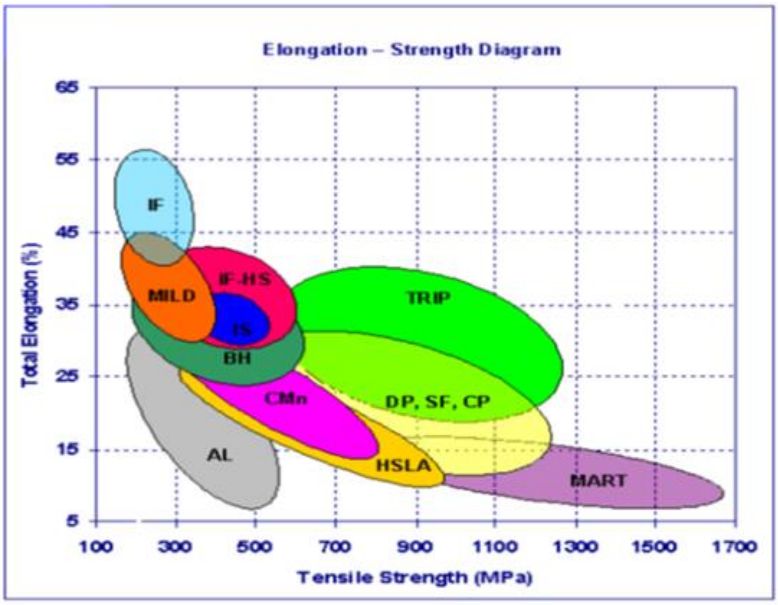


Fig 2.1: Formability Chart: Material Based on Strength and Elongation [2]

The tensile properties of bake hardening steels are compared with those of other grades in Fig. 2.1 [2] of steel, which also indicates the direction in which properties must develop to meet the demands of the automotive sector. Bake hardening steels have a low proof stress and good formability at initially, making them suitable for the more complex forming operations encountered during fabrication of outer body parts. During forming and paint baking, the steel will age significantly, resulting in the return of discontinuous yielding accompanied by an increase in the yield strength. Figure 2.2 [3] illustrates how this strength increase compares with that achieved with a formable IF steel and a high strength rephosphorised steel. It can be seen that the use of bake hardening steel can result in both good shape fixability and improved dent resistance in the final component. Since the strength increase occurs after the component has been formed, thinner material can be used for components such as fenders, bonnets, boot lids, and door outers for resulting in a weight saving of ~ 7 kg per car. Components such as boot lids and bonnets that experience relatively small deformations during forming benefit particularly from the use of a bake hardening steel, as the relatively small strength increase produced by work hardening can be improved with a larger bake hardening increase. Resistance to small dents caused by stones and other debris is also of importance, with parts such as bonnets and outer door skins being the most susceptible. Bake hardening steels can offer superior dent resistance to both static and dynamic denting, compared with other steel grades, because of their increased strength after baking.[4]

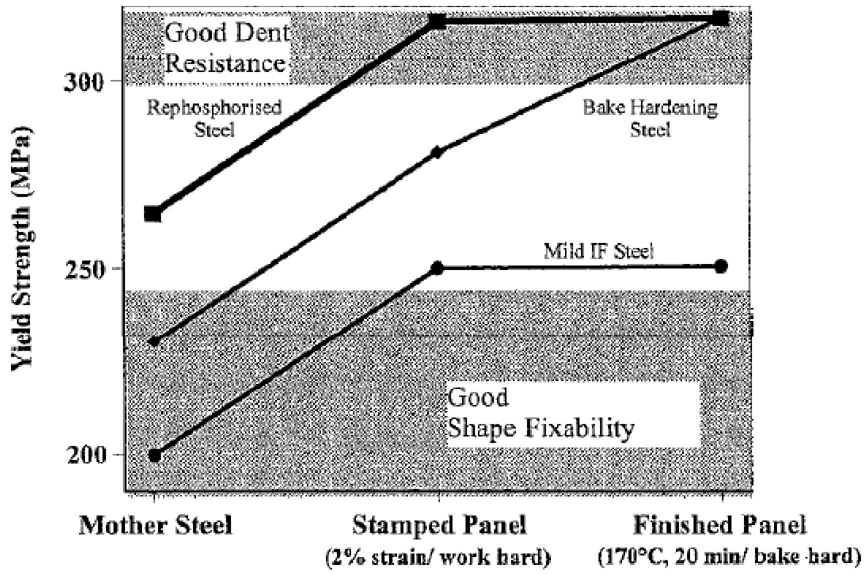


Fig 2.2: Schematic illustration of bake hardening concept in fabrication of automotive body parts [3].

2.1.2 Metallurgical aspect of bake harden steels

Bake hardening essentially a high temperature strain aging process, it a diffusion controlled process involving the migration of solute atoms within the iron lattice. The diffusion of these atoms will be affected by temperature, time and the amount of free carbon and nitrogen atom present in the steel. Some Factors such as grain size and dislocation density may also have an influence due to the plastic deformation and heating. Studies on the fundamental mechanisms of bake hardening (strain aging) will be reviewed with an emphasis on how these may relate to modern ULC chemistries.

2.1.3 Mechanism of bake hardening

The mechanism of bake hardening is diffusion process of solute atom and reformation of Cottrell atmosphere. The yield strength increase due to the bake hardening is accompanied by the reappear of the yield point and yield point elongation; there may also be a slight increase in tensile strength and decrease in elongation. To realise this strength increase, the following criteria must be satisfied.

(i) Mobile dislocations are must be present in the steel.

(ii) There must be sufficient concentration of solute in the steel to pin these dislocations.

(iii) The solute atom like carbon and nitrogen must be free to move at the aging temperature.

(iv) Segregation of carbon atoms to formation of the Cottrell atmosphere.

(v) Dislocation recovery must be sufficiently slow to prevent softening.

The driving force for pinning is a reduction in lattice energy. Both impurity atoms and dislocations induce lattice strains in the iron matrix and these strains can be relaxed if the interstitial atoms diffuse to the vicinity of dislocations. [5]

2.1.4 Factors affecting Bake Hardening

The bake hardening behaviour of ultra- low carbon steel affected by many parameters, like as baking temperature and time, amount of pre-strain level , sufficient amount of solute atoms, grain size , amount of free dislocation present etc. These parameters may have an effect on kinetics of carbon diffusion and the dislocation density etc.

2.1.4.1 Interstitial solute atom (carbon and nitrogen)

One of the most impotent phenomena of BH grade steel is its “shelf life”. Auto- makers are mostly focused about this particular property as this is the ability of the steel to resist room temperature aging during storage. The necessity is that the steel should possess sufficient "shelf life" so that the material should not undergo aging and deteriorate throughout transportation and storage before the last utilization. This most important parameter of the auto-makers in order to control the inventory and produce the components without any rejection. At least 3 months “shelf life” is expected by the component makers and this might be controlled predominantly by controlling the diffusion of interstitial elements.

The most essential interstitial solutes which may be found in steels are nitrogen and carbon. Between this two elements, nitrogen is very much deleterious because it causes room temperature aging [6]. This kind of room temperature aging leads to the formation of Lüders band (stretcher strains) which is not acceptable for exposed auto-body parts. The composition of BH steels is in this manner composed in such a path, that the solute nitrogen is eliminated to avoid the room temperature aging and BH effect is controlled through the amount of carbon only. With increasing the amount of solute carbon in steel, BH response should also increase. This is because of the fact that with increasing solute carbon in steel, more solute is available to pin mobile dislocations and the formation of clusters will occur more rapidly. [7] showed that an increase of carbon from 0 to 40 ppm increased the BH response from 80 to 150MPa but further increase in solute carbon had no effect in BH response .

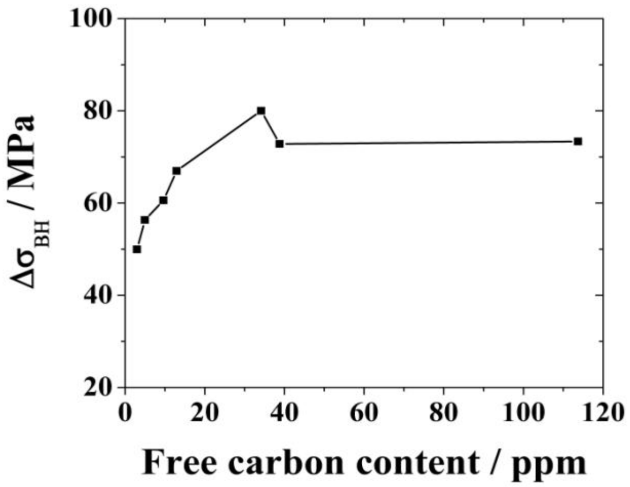


Fig 2.3: Effect of Interstitial solute content (Carbon atom) in bake hardening response [8]

2.1.4.2 Effect of Pre-strain

Most of the auto body parts experience a little measure of pre- straining throughout the last framing operation before the baking process. The BH experiments are, therefore, carried out by subjecting the samples to a small amount of pre-strain at room temperature. A tensile pre-strain of 2% has been found reasonable for this purpose [9]. The application of pre-strain level to the specimens effect the dislocation density. Additional dislocations generated during pre-straining are pinned by free solute atoms that diffuse to the dislocation core during baking and as a result YS increases.

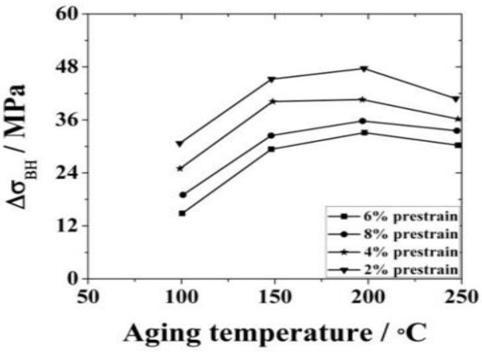


Fig.2.4: Effect of temperature and strain on the bake hardening values [7].

2.1.4.3 Baking temperature and time

Bake hardening is directly related to diffusion process of interstitial solute atoms, the basically solute atom are carbon and nitrogen the diffusibility of these atom depend on baking temperature and time . So we are expected that bake hardening response would depend on baking temperature and time.

The bake hardening response of BH grade steel is a function of both time and temperature and pre-strain level**.** The automobile industries maintain a standard schedule for the bake hardening process during the paint baking cycle. In a temperature range, where recovery of the cold worked structure is negligible, the Strength increases at a constant temperature asymptotically with time and at a constant time, exponentially with temperature [10]. In experiments with a low carbon (0.03 wt.%) BH grade steel at different aging temperatures, it was found that the beginning of the second stage at 180˚C occurred 20 minutes earlier compared to the results at 150 ˚C [10]. At lower baking temperature (50-120˚C), the first step of hardening had a dependence on aging time. However, at higher temperatures (> 120˚C), the first step gets completed within a very short period of time. Other researchers also found similar results during their experiments with Ti stabilised Ultra Low Carbon (ULC) grade steels [11]. Some have proposed that there exists an incubation time of about 30 minutes before any appreciable change in YS is observed at lower baking temperature [12]. The maximum increase in YS in the second stage at a constant pre strain level was found to be independent of the aging temperature provided the aging treatment was sufficiently long (Fig. 2.4). However, according to [13], though the first stage of BH is independent of pre-strain, the second stage showed a deterioration in strength increment with increasing pre-strain.

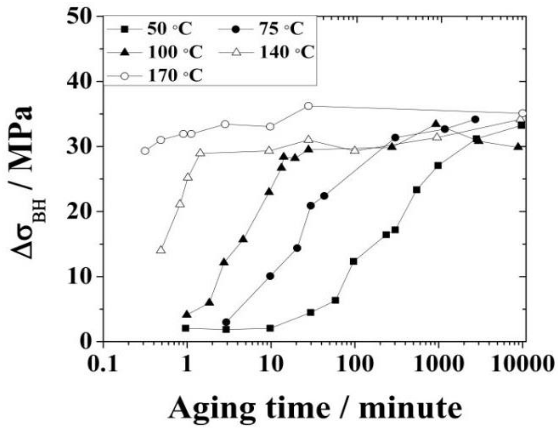


Fig. 2.5: BH response at different aging temperature for a 5different pre-strained sample [14].

2.1.4.4 Effect of strain rates

Strain rate is the rate of change in strain (deformation) of a material with respect to time. In the mathematical way strain rate are show as $\dot{\varepsilon}=\frac{\partial \varepsilon}{\partial t}$ and the units of strain rate is s^{-1}, i.e. per second. Bake hardening is also affected by the strain rateat higher strain rate testing material become harder due to more no of free dislocation is generated. So dislocation density will increase this will affect the movement of dislocations. Dislocation is not able to easily move at the result material become harder and yield strength will some higher compare to slower strain rate.

2.1.4.4.1Tensile testing

Tensile tests are conducted at a specific strain rate. Since change in the strain rate affects the tensile properties, different regimes of strain rate are divided into different categories as shown in Fig:2.6.

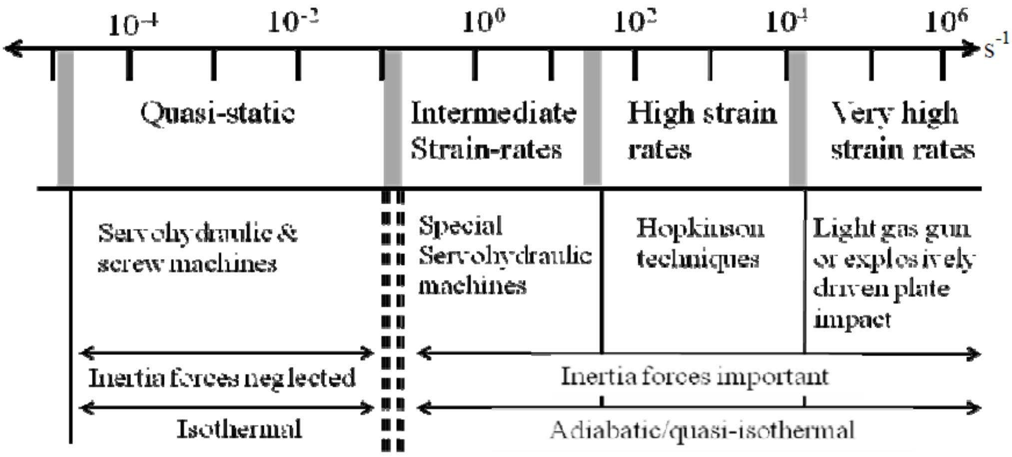


Fig 2.6: Strain rate regimes and associated instruments.

2.2 Dislocation density: A brief review

2.2.1 Introduction

A dislocation is a crystallographic defect, or irregularity, within a crystal structure. The presence of dislocations strongly influences many of the properties of materials. The theory describing the elastic fields of the defects was originally developed by [15] but the term 'dislocation' to refer to a defect on the atomic scale was coined by [16]. Some types of dislocations can be visualized as being caused by the termination of a plane of atoms in the middle of a crystal. In such a case, the surrounding planes are not straight, but instead they bend around the edge of the terminating plane so that the crystal structure is perfectly ordered on either side. The analogy with a stack of paper is apt: if half a piece of paper is inserted in a stack of paper, the defect in the stack is only noticeable at the edge of the half sheet.

2.2.2 Dislocation density

The dislocation density (ρ) is a key microstructural parameter since it is strongly related to mechanical properties of metals and alloys. The dislocation density in metals can be significantly changed during plastic straining, thermal annealing or when they undergo phase transformations such as the martensitic transformation found in Fe–C steels**.** In deformed metals, the stored energy provided by dislocations is the driving force for important solid-state reactions like recovery and recrystallization [17]. Furthermore, the quantitative evaluation of the dislocation density in metals is also very important in the development of theories of plastic deformation [18].

Among the several experimental techniques to evaluate the dislocation density in metals, direct and indirect methods are usually reported including Vickers hardness testing, **X-ray diffraction line profile analysis**, evaluation of etch pits, transmission electron microscopy (TEM), flow stress, magnetic (coercive field) and electrical resistivity measurements [19]. TEM and X-ray diffraction line profile analysis are the most recommended techniques to quantify the dislocation density, while; for instance, coercive field and resistivity are strongly affected by factors as precipitates and solutes.

The choice of the method to evaluate the dislocation density by using X-ray or TEM depends on the magnitude of dislocation density and the nature of the dislocation array. For instance, in severely deformed metals where very high dislocation densities are found in a complex substructure, TEM is less advisable since counting of individual dislocations by using quantitative metallographic methods becomes quite difficult. This difficult can be overcome by using X-ray diffraction. On the other hand, in less deformed metals or in creep-tested specimens, the TEM becomes more reliable than X-ray diffraction since the elastic distortion caused by dislocations in the lattice and consequent peak broadening is very small.

CHAPTER -3: Experimental

CHAPTER -03 EXPERIMENTAL

3.1 Material

The material used in present study was**BH220** Bake hardening steel obtained from Tata Steel as sheets of 0.6 to 0.65 mm thickness. The composition of steel has been ascertained by optical emission spectroscopy and is given in Table 3.1

Table 3.1: Chemical composition of BH 220 Steel

C	Mn	S	P	Si	Al	Cr	Ni	Nb	Cu	Fe
0.0027	0.38	0.009	0.72	0.004	0.048	0.016	0.014	0.001	0.005	Balance

3.2 Microstructural characterization

The study related to microstructural features has been performed on BH 220 steel to reveal the phases present in the steel. The as received material was cut into small pieces for microstructural examination. Metallographic sample preparation was done in transverse and longitudinal direction (with reference to the as received rolling direction). Standard metallographic technique was used to prepare the samples. Miror polished samples were etched with 4% Nital solution to reveal the microstructure. The samples were examined with optical and scanning electron microscopes.

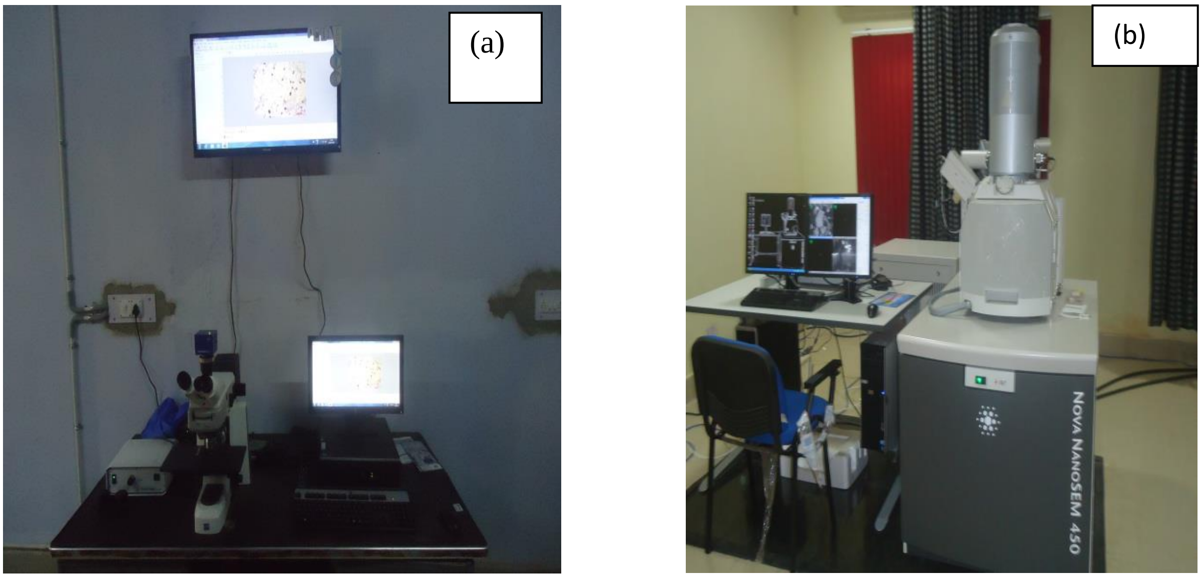


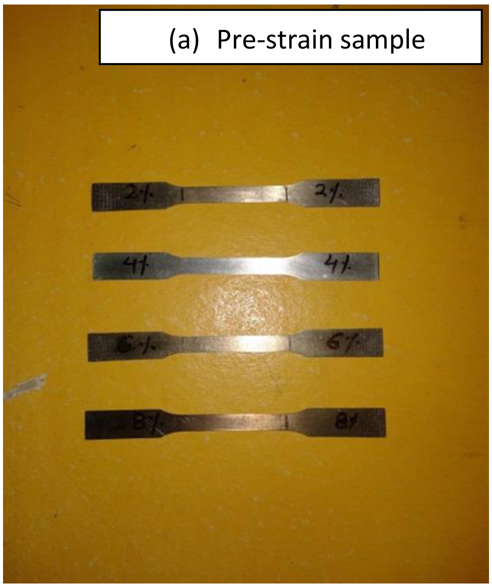
Fig. 3.1 (a) Optical microscope microscopes (b) Scanning electron microscopes.

3.3 Average grain size measurement

The micrographs obtained from microstructural observatuon was analysed to asses the average grain size and grain size distribution. The average grain size was determined using planimetric method as described in ASTM standard E112[20]. This method inscribes a circle of known area accros the grain boundary on the micrograph or the ground glass screen of the metallograph. Magnification of 100X revealed more than 100 grains in the field which would be counted and thus grain size was determined from metallographs at 100X magnification. The sum of all the grains included completely within the known area plus one half the numbers of grains intersected by the circumference of the area gives the number of equivalent whole grains, measured at the magnification used, within the area. This number when multiplied with appropriate Jeffries multiplier, (as mentioned in ASTM standard E112), gives number of grains per unit area which is used to determine the ASTM grain size number.

3.4 Pre-strain and pre-strain with bake hardening

To measure the pre-strain and pre-strain with bake hardening effect during the tensile test at quasi-static strain and high strain rates the samples were subjected to these process. Two sets of samples were taken for each strain rate of testing. All the samples are subjected to pre-strain at 0.001/s strain rate at a paticular pre-strain level (2, 4, 6 and 8%). One set of samples are subjected to direct tensile test at different strain rates. The second set of samples were baked in oven at 170^{o}C for 20 minutes followed by tensile test at different strain rates.


(a) Pre-strain sample

(b) Hot air oven

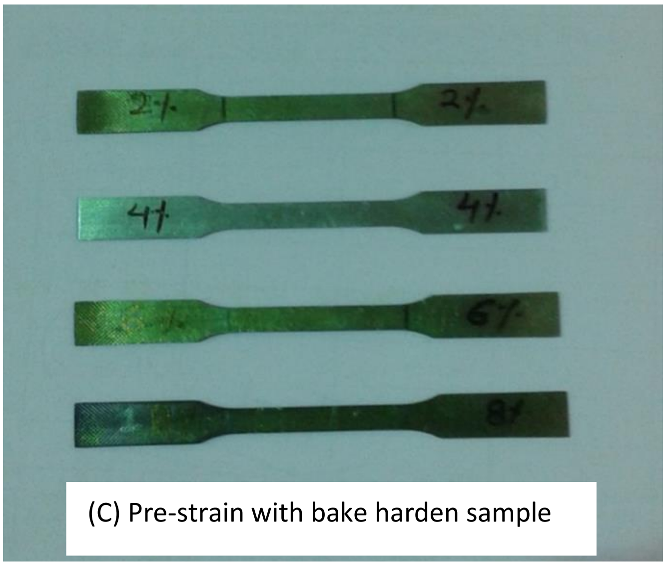


Fig. 3.2 (a) Pre-strain sample (b) Hot air oven (c) Pre-strain with bake hardening sample

3.5 Design of Exepriments

To examine the bake hardening (BH) effect, tensile tests were planned at quasi-static and high strain rates. The matrix of exepriments designed on the basis of strain rate and pre – strain level is shown in the table no.3.2

Table no.3.2 Design of Expriments quasi-static and high strain rates

Quasi-static strain rate				High strain rate	
Strain rate 0.001/s		Strain rate 0.1/s		Strain rate 100/s	
Pre-strain	Pre-strain with bake hardening	Pre-strain	Pre-strain with bake hardening	Pre-strain	Pre-strain with bake hardening
0%	0%	0%	0%	0%	0%
2%	2%	2%	2%	2%	2%
4%	4%	4%	4%	4%	4%
6%	6%	6%	6%	6%	6%
8%	8%	8%	8%	8%	8%

3.5.1 Tesnsile testing at quasi-static strain rates

The dimension of the test samples used in the quasi-static strain rate testing is shown in Fig. 3.3.(a) The gauge length and width of the specimens were kept as 30 mm and 6 mm respectively according to the configuration of sub-size sheet specimens as recommended in ASTM standard E- 8M, [21]. The tensile tests were carried out using a 100 kN capacity servo-hydraulic INSTRON testing machine (Model No.-8501) (Fig. 3.3 (b))

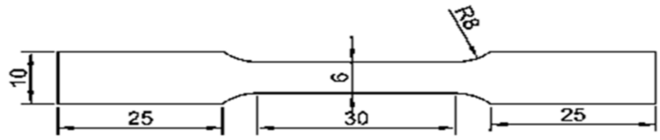


Fig.3.3 (a): Schematic of the tensile specimen for Quasi-static strain rates (0.001/s) (All dimensions are in mm) [21]

Fig.3.3 (b) Servo-hydraulic INSTRON testing machine (Model No.-8501)

3.5.2 Tesnsile testing at high strain rate test

The dimension of the test samples used in the high strain rate testing is shown in Fig. 3.4(a). Here, 16mm is gauge length of the sample, 7 to 7.05 are the width of the sample and 0.6 to 0.65 are the thickness of the sample. High strain rate testing of the obtained samples were conducted in INSTRON VHS 8800 servo-hydraulic testing machine Fig.3.4(b)

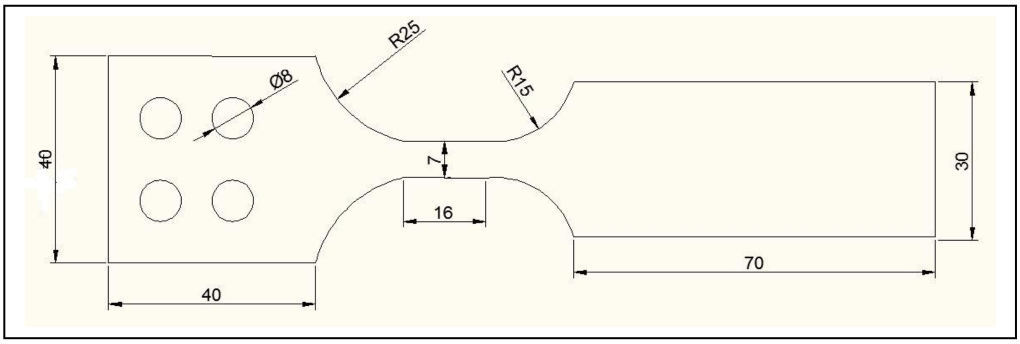


Fig 3.4(a) Typical tensile test specimen used for high strain rate testing

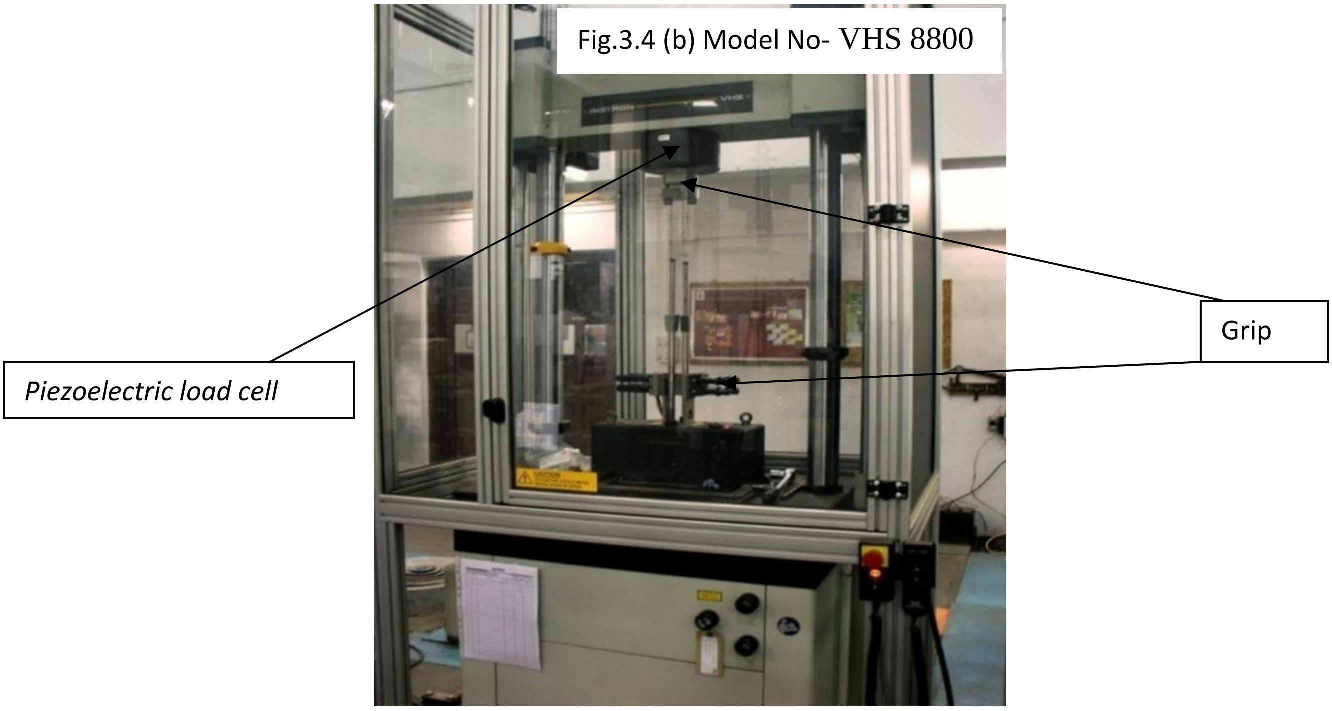


Fig.3.4 (b) INSTRON VHS 8800 servo-hydraulic testing machine

3.6 Fractography

The fractured surface of the failed test spacemen of each sample was observed under Field Emission Scanning Electron Microscope (FESEM) (NOVA NANOSEM 450 FEG WITH EDS FROM BRUKER) in secondary electron mode.

3.7 Calculation of dislocation density

Estimation of dislocation density in theBH220 steel was carried out in as received condition, before and after of the tensile testing at quasi –static strain rates (0.001/s and 0.1/s) by X-ray diffraction techniques using Phylips X-ray diffracto meter (model: PW3040/00 X-Pert PAN alytical) fitted with a copper target (wave length: 0.15 nm).

The dislocation density can be measured by X-ray diffraction experiments by the following way. The integral breadths of the diffraction profiles were evaluated by a modified Williamson–Hall plot in quadratic form (1)

$$\Delta k = \frac{1}{d} + \frac{\pi M^2 b^2}{2} \rho^{\frac{1}{2}} (k^2 \overline{c}) + 0(k^2 \overline{c}^2) \qquad (1)$$

Where

$\Delta k = 2\,cos\,\theta\;\Delta\theta/\lambda$, k= $2cos\,\theta/\lambda$, θ and $\Delta\theta$ are diffraction angle and the integral breadth of diffraction peak, b = Burgers vector in (nm), d is the average grain size and ρ is the dislocation density. M is a constant parameter depending on the effective outer cut off radius of dislocation and O indicates non-interpreted higher order terms.

The value of C represents the average contrast factor of the dislocations for particular reflection. The average contrast factor for different diffraction vectors are defined as

$$C = C_{h00}\left(1 - q\,\frac{h^2k^2 + k^2l^2 + l^2h^2}{h^2 + k^2 + h^2}\right) \qquad (2)$$

Where the value of C_{h00} average contrast factor corresponding to *h00* reflection. The value of C_{h00} = 0.29855obtained from the given method at Ungáretal [22]

With the help of above two equations (1 & 2) dislocation density of the BH220 steel was calculated at each condition and at each steps of testing.

CHAPTER-4: Results and discussion

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Microstructural study of the as received steel

The Fig. 6 (a) shows the optical microstructure of the as received BH 220 steel. The figures tell that the steel is predominantly single phase i.e. ferritic in nature. The micrograph was analysed by standard image analysis software and the grain size distribution obtained by that is displayed in Fig. 6(b). Average grain-size of ferrite was estimated as 33.75μm.

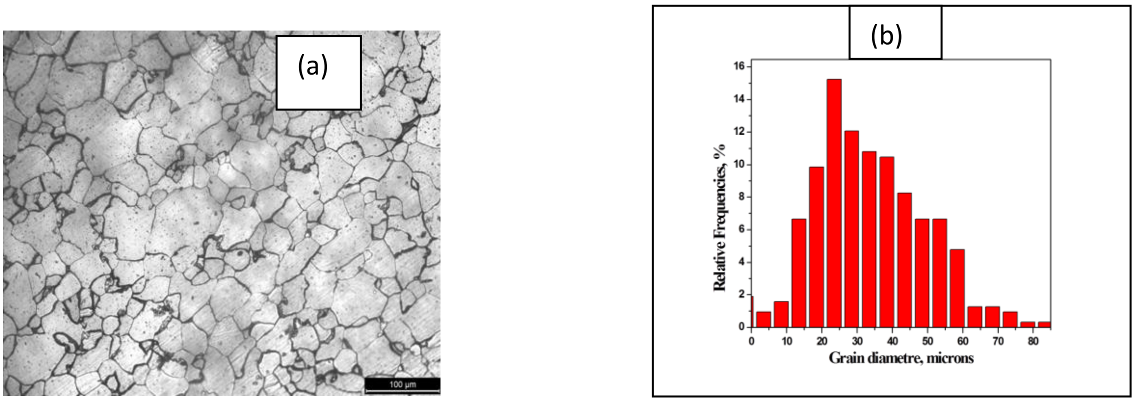


Fig. 4.1: (a) Microstructure of the as received BH220 steel, (b) Average distribution grain size

After optical study the steel was also analysed by SEM. SEM images were captured for both normal and transverse diraction of rolling diraction as show in Fig. 4.2 and 4.3.

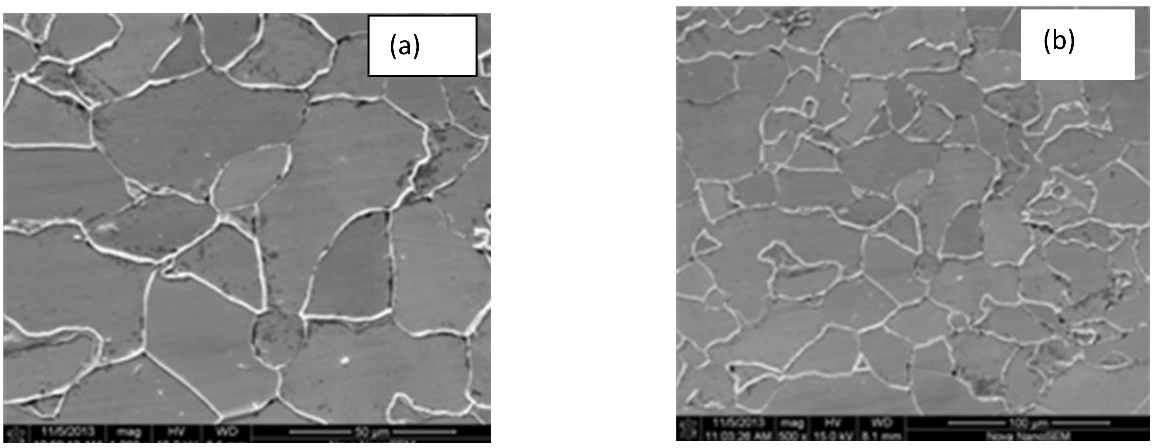


Fig. 4.2: SEM micrograpgh of RD-TD plane at (a) 500x and (b) 1000x maganification.

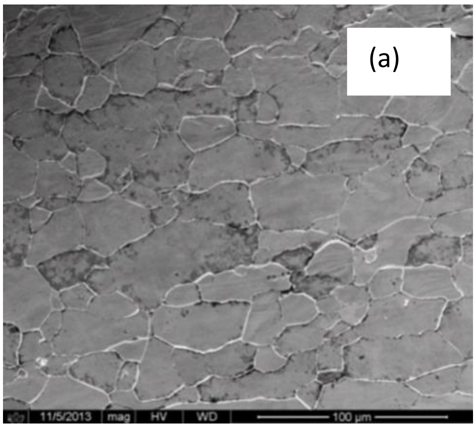


Fig. 4.3: SEM micrograph of RD-ND plane at 600x maganification.

It can be observed from the figures that the grains are same uni-diractional in nature and elongated in normal diraction .

4.2 Effect of pre-strain on tensile properties, with and without and bake hardening

4.2.1 Quasi-static strain rates

The Engineering stress–strain plots of the samples with pre-strain and bake hardened condition tested at 0.001/s and 0.1/s strain rates are shown in Fig. 4.4(a) and (c). Similarly, stress–strain plots of the samples with pre-strain and tested at 0.001/s and 0.1/s strain rates are shown in Fig. 4.4(b) and (d). Bake hardening is a process of strain aging. Thus the results show that the bake hardenability of steel increases with increasing pre-strain level and strain rate. The yield strength is higher at higher strain rate because carbon in iron is an interstitial impurities, but the interstitial voids is much smaller than the size of carbon atom, due to baking carbon diffuses to the dislocation site. Although the interstitial void at the dislocation side is slightly bigger but still carbon or nitrogen will produced strain field. This carbon and nitrogen rich atmosphere at the dislocation site is called Cottrell atmosphere. Upon application of the load it requires extra stress to break the Cottrell atmosphere. So yield strength is increasing during bake hardening. In the case of pre-straining (pre-strain at work hardening region) the yield point in appeared in pre-strain process the sample is unload and again loading the yield point will not appeared because of absence of C at the dislocation site. Tabular data of all the tests are summarised in table 4.1and 4.2.

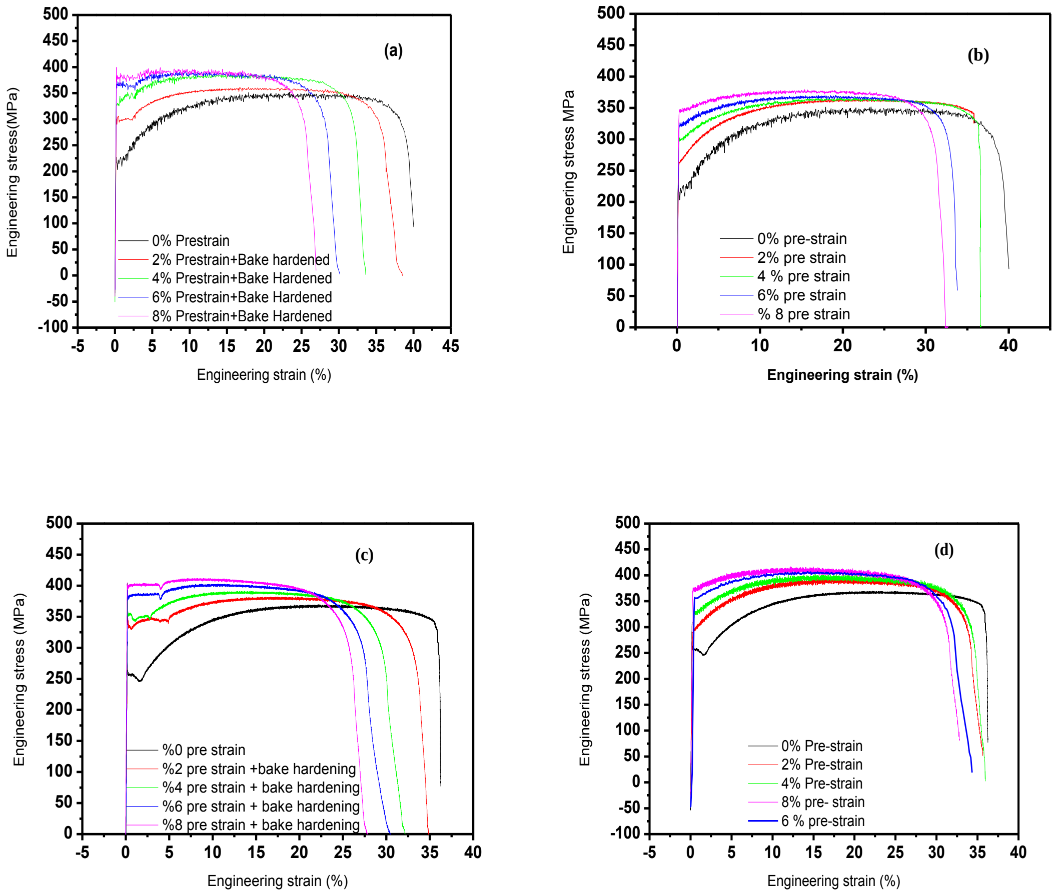


Fig. 4.4: Bake hardening behaviour and pre-strain behaviour of BH220 steel at 0.001/s and 0.1/s strain rates.

Table 4.1: Yield strength and ultimate tensile strength at 0.001/s strain rate

Strain rate 0.001/s	Yield strength (MPa)	Yield strength (MPa)	Ultimate tensile strength(MPa)	Ultimate tensile strength(MPa)
Pre –strain level	Strain rate 0.001/s	Pre-strain + bake hardening	Pre -strain	Pre-strain + bake hardening
0%	223	223 (without bake)	351	351(without bake)
2%	266	301	361	363
4%	299	337	366	371
6%	320	360	370	392
8%	348	373	379	399

Table 4.2: yield strength and ultimate tensile strength at 0.1/s strain rate

Strain rate 0.1/s	Yield strength (MPa)	Yield strength (MPa)	Ultimate tensile strength (MPa)	Ultimate tensile strength(MPa)
Pre-strain level	Pre-strain	Pre-strain + bake hardening	Pre –strain	Pre-strain + bake hardening
0%	237	237	368	368
2%	297	341	394	381
4%	344	349	401	391
6%	357	377	406	402
8%	375	395	415	412

4.2.1.1 Yield strength variation

To enumerate the effect of bake hardening and pre-strain on the yield strength, variation of YS with different pre-strain and BH value is plotted in Fig. 4.5. It can be observed from the plot that the YS values increases with pre-strain value almost linearly for a particular test condition. It can also be observed that at higher strain rate yield strength value is more compared to slower strain rate value. For example, in case of as received steel the yield strength value at 0.001/s strain rate is 223 MPa, whereas at 0.1/s strain rate it is 237 MPa. We can also observe that in every condition the increase in the yield strength follows the same trained at both strain rate and all pre-strain level. The maximum variation in yield strength in all condition is 223 to 395 MPa.

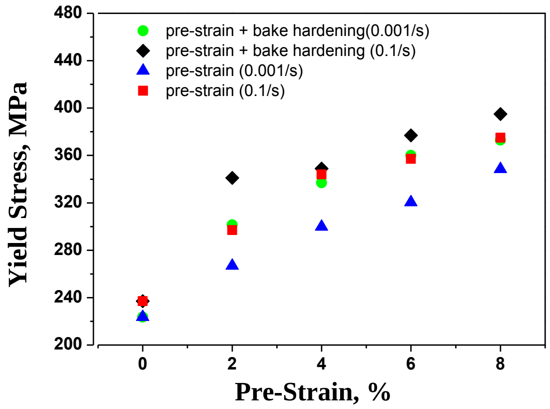


Fig. 4.5: Yield strength variation of BH220 steel at 0.001 /s and 0.1/s strain rate with different pre-strain and BH condition.

4.2.1.2 Ultimate tensile

Fig . 4.6 shows the nature of ultimate tensile strength variation at 0.001/s and 0.1/s strain in pre-strain and pre-strain with bake hardened condition. It can be observed that the variation of ultimate tensile strength in both cases fallow same nature as in case of yield strength variation. At the strain rate of 0.001/s and 0.1/s the ultimate tensile strength of base sample is 351 and 368 MPa respectively.

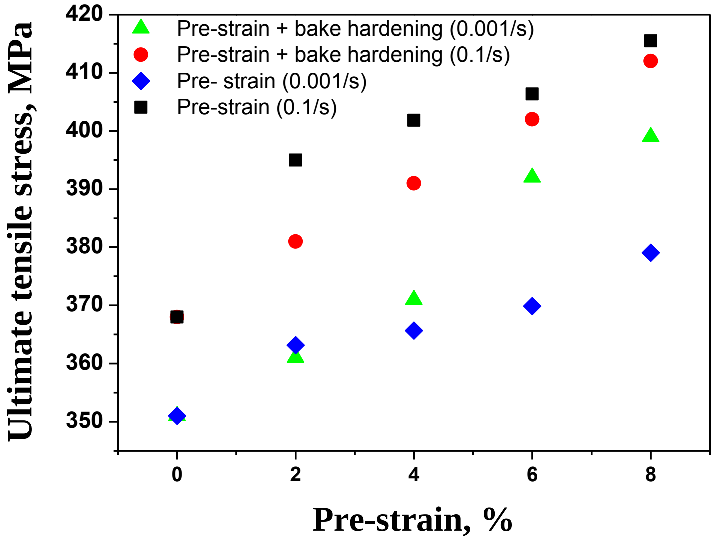


Fig. 4.6: Ultimate tensile strength behaviour of BH220 steel at 0.001 /sand 0.1/s strain rates with different pre-strain and BH condition.

4.2.1.3 Uniform elongation

During the tensile testing's, the % of elongation was measured at UTs point. Such values of the entire specimen were plotted in Fig. 4.7. In that it can be observed that % elongation is maximum in base sample. With increase in pre-strain level the % elongation decreases, but at the same time it increases with the strain rate. The % elongation of bake and unbaked sample was clearly showed in the figure. The baked sample had less % elongation compared to the unbaked (only pre-strained) one. The trend is just opposite of Y.S. and UTS as expected. With increase in BH response the ductility of the samples deteriorates due to increase in pinned dislocation density.

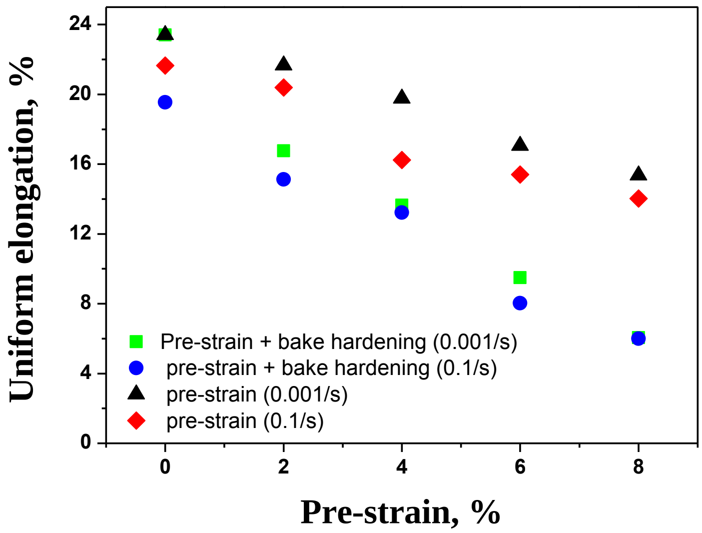
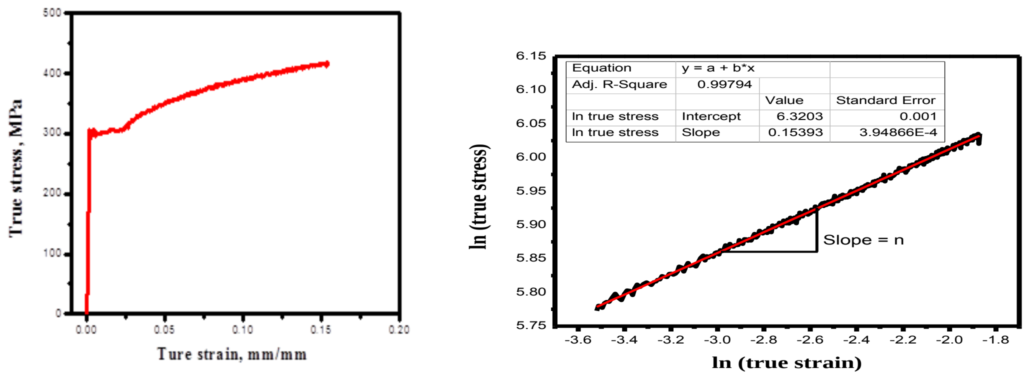


Fig. 4.7: Elongation behaviour of BH220 steel at 0.001/s and 0.1/s strain rate

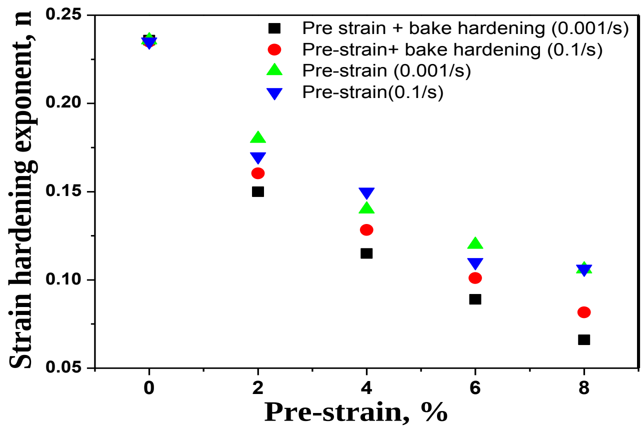
4.2.1.4 Strain hardening exponent (n)

For each tensile test, strain hardening exponents (n) were calculated with the help of true stress-strain plot. The typical true stress-strain plot and its slopes are show in Fig. 4.8 (a) and (b).

The calculated *n* values were plotted pre-strain and other variation in Fig. 4.8 (c). From the plot it can be observed that with increase in strain rate, strain hardening exponent increases but it decreases at increasing value of pre-strain. This can be attributed by the phenomena described in section 4.2.1.



(a) (b)

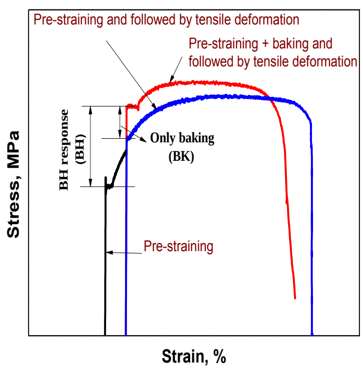


(c)

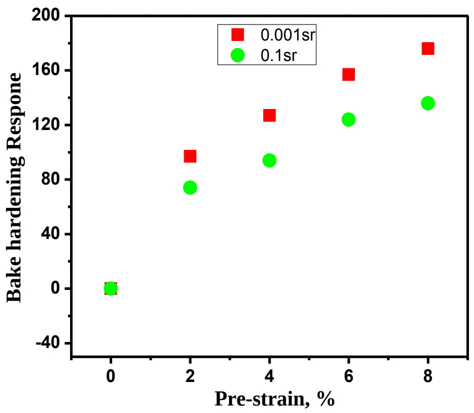
Fig. 4.8: (a) True stress-strain plot, (b) strain hardening exponent (*n*) calculation, (c) variation of *n* with pre strain and strain rate of the testing.

4.2.1.5 Bake hardening response

Increase in Yield strength value due to pre-strain and baking is known as Bake Hardening response and the same shown in Fig. 4.9(a). BH response of the present steel is significant in nature variation of the response with pre-strain and strain rate is showed in Fig. 4.9(b). From the plot it is clear that baking has significant effect in increasing the yield strength of the virgin material. It can also be observed that the BH response increases with pre-strain and strain rate of testing. During baking the carbon and nitrogen atom diffuse to the dislocation sites and pin them which results in increase in the Y.S. The BH response also increases with the pre strain and that is obvious as more amount of pinning is possible in high pre strained samples. But it was observed that with increase in strain rate the BH response decreases.



(a)



(b)

Fig. 4.9: BH Response behaviour of BH220 steel (a) calculation example of BH response, (b) BH response at 0.001/s and 0.1/s strain rate.

4.2.1.6 Fractographic study

SEM photographs of the fracture surface of the as received steel tested at 0.001/s strain rate are displayed in Fig. 4.10. The fractorgraphic observation at strain rate of 0.001/s reveals mixed mode of fracture. This type of fracture surface is generally observed in bcc materials with ductile –to- brittle transition based on the dislocation concepts.

The dislocation theory of brittle fracture consists of the stages.

1. Plastic deformation which involves the pile-up of dislocation along their slip plane at an obstacle.
2. The build-up of shear stress at the head of the pile-up to nucleate a micro crack.
3. In some cases the stored elastic strain energy drives the micro crack to complete the fracture without further dislocation movement in the pile – up. More typically in metals, a distinct growth stage is observed in which an increased stress is required to propagate the micro-crack; thus the fracture stress is the stress required to propagate the micro-cracks.[23]

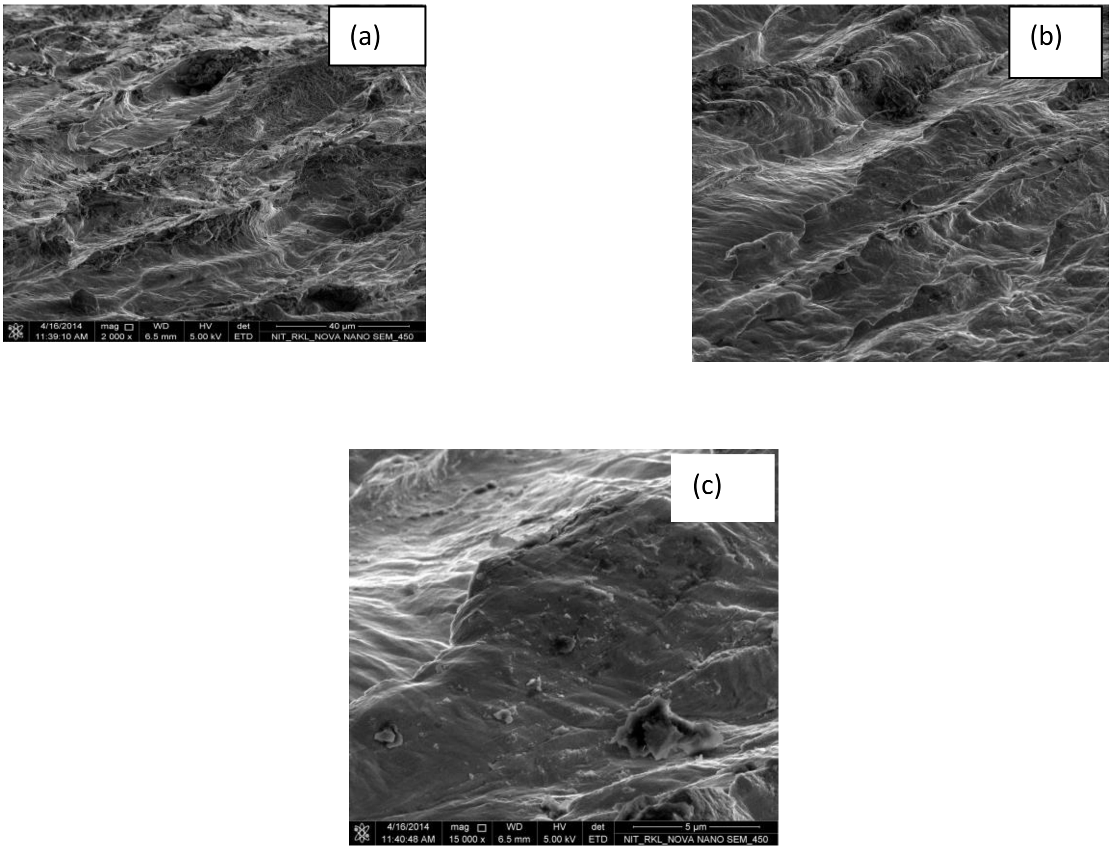


Fig. 4.10: Fractorgraphic images obtained after testing at 0.001/s strain rate with different magnification.

The fractorgraphic observation at 0.1/s strain rate is shown in FIG. 4.11. The type of fracture observed here was mixed type in nature. This type of facture is called quasi-cleavage fracture. This mixed type of facture surface was not truely cleavage fracture nor dimple rupture. This observation suggests that ductile-shear fracture may be the prominent mode of deformation for the selected material when these are tested at high strain rate.

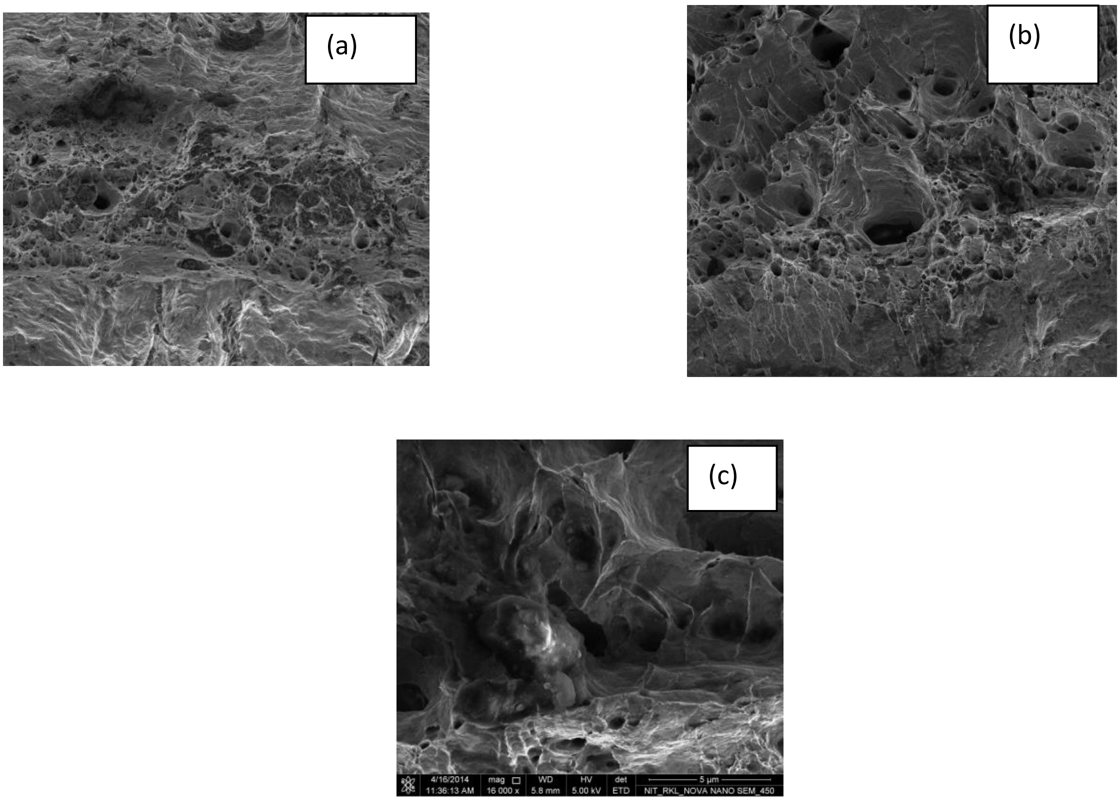


Fig. 4.11: Fractorgraphic images obtained after testing at 0.1/s strain rate with different magnification.

4.2.2 High strain rate (100/s)

Fig. 4.13 shows the engineering stress-strain plot at strain rate 100/s. Dynamic tensile properties of the selected steels was evaluated at this high strain rate value. The load-time plots generated from specimens tested at high strain rate test were found to contain appreciable amount of noise. This external noise appears to originate due to sudden engagement of the lower grip at very high speeds during the process of loading. A typical load-elongation plot generated by tensile test at strain rate of 100/ s is shown in Fig. 4.13 and it is clearly visible that external noise is prominent in the plastic region of the tensile stress-strain curve. Presence of external noise hinders estimation of the actual material deformation characteristic, which remain engulfed within the external noise. Thus attempts were made to separate out the noise signal from the original data.

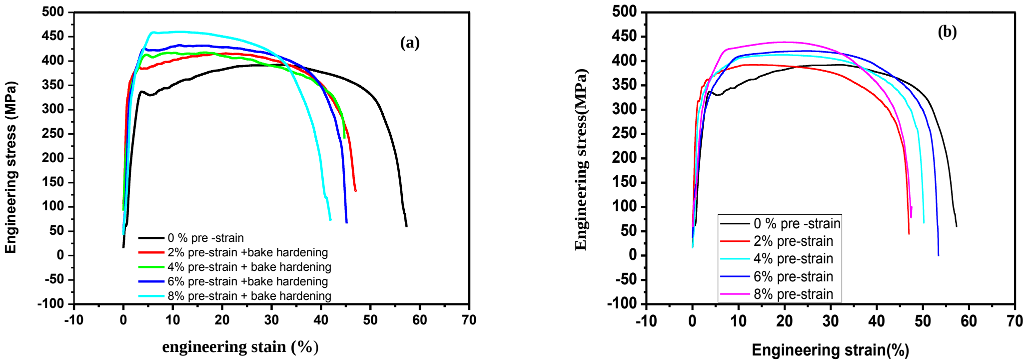


Fig. 4.12: (a) bake hardening behaviour (b) pre-strain behaviour at 100/s strain rate.

4.2.2.1 Yield strength

Fig. 4.13 shows the comparative study of yield strength of high strain rate samples in both bake hardened and without bake hardened (only pre strained) conditions. The nature of result fallows the similar pattern as observed in quasi-static strain rate but the value of yield strength increases rapidly.

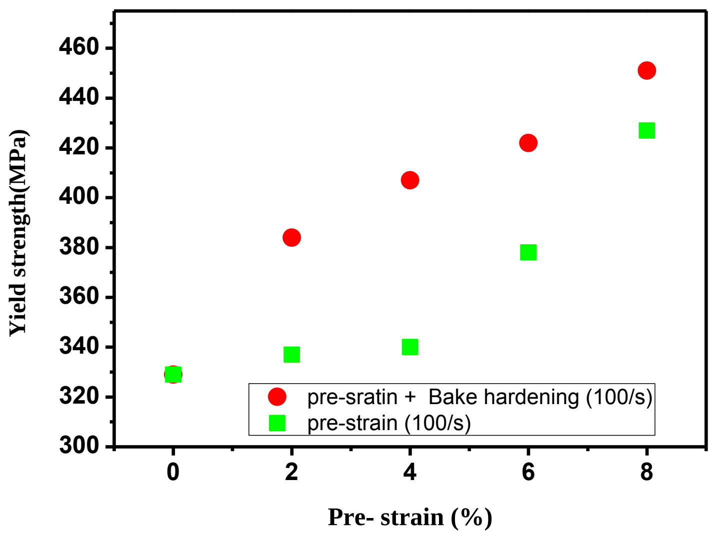


Fig. 4.13: Yield strength behaviour at 100/s strain rate with different pre-strain level.

4.2.2.2 Ultimate tensile strength

Fig. 4.14 shows the comparative study of ultimate tensile strength of high strain rate samples in both bake hardened and without bake hardened (only pre strained) conditions. The value of ultimate tensile strength varies from 390 to 465 MPa.

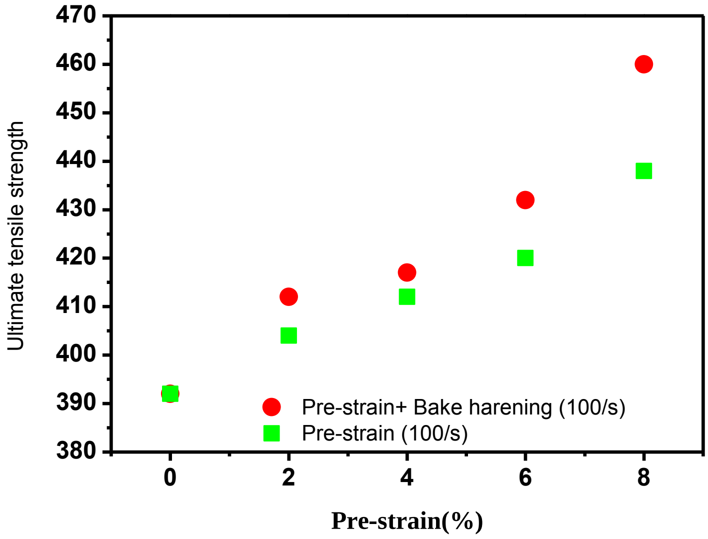


Fig. 4.14: Ultimate tensile strength behaviour at 100/s strain rate with different pre-strain level.

4.2.2.3 BH Response

BH response observed at high strain rate is shown in Fig. 4.15. It shows that the response is increasing in nature with increasing value of pre-strain. At the 8% pre-strain the response value was maximum (120MPa).

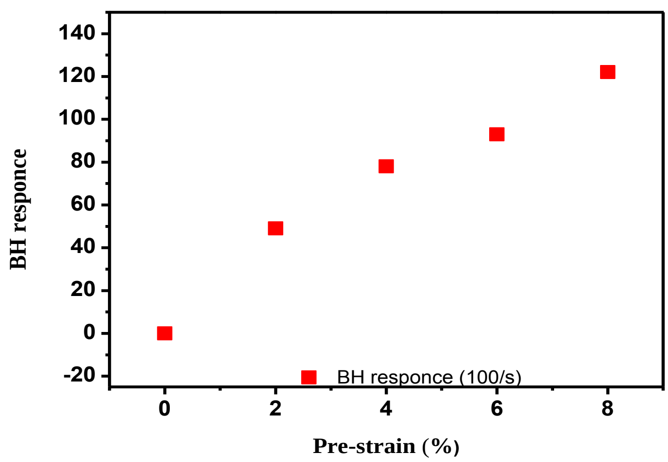


Fig. 4.15: Bake hardening response at strain rate 100/s

4.3 Comparative study of mechanical properties at quasi-static and high strain rates

Fig. 4.16 shows the yield strength values of bake hardened samples tested at both situations (quasi-static and high strain rate). The observation clearly shows that this steel has higher dent resistance at higher strain rate and pre strain can increase the property further.

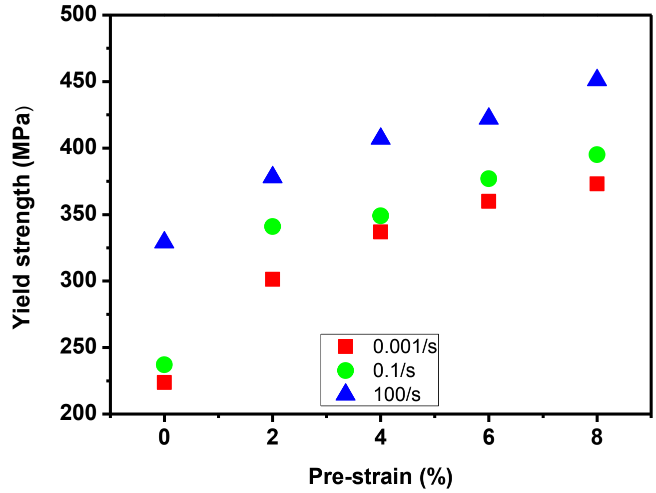


Fig. 4.16: Yield strength of BH 220 steel at quasi-static and high strain rates

Similar cooperative data was observed in case of UTS also. The same is represented in Fig. 4.17. So, even at high strain rate value separate trend or mechanism could not be predicted.

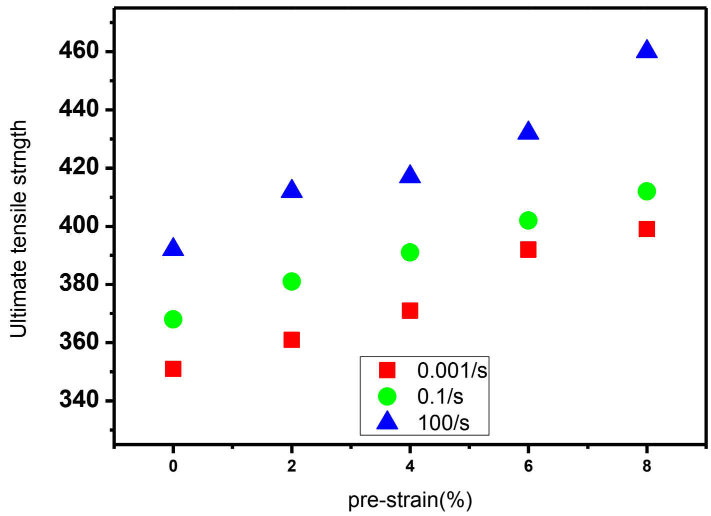


Fig. 4.17: Ultimate tensile strength of BH220 steel at quasi-static and high strain rates with different pre-strain level.

Fig. 4.18 shows the bake hardening response of BH220 steel at quasi-static and high strain rates. The BH response value decreases at increasing the strain rates. Thus, the response is maxima at strain rate of 0.001/s in each level of pre-strain condition.

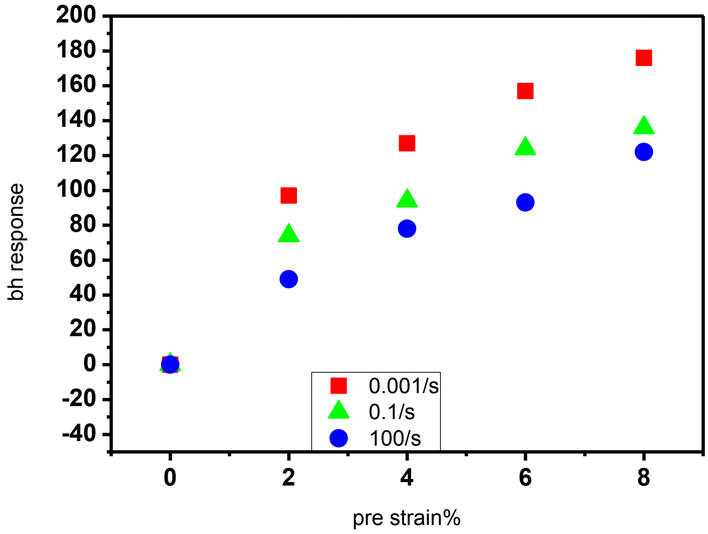


Fig. 4.18: Bake hardening response of BH220 steel at quasi-static and high strain rates with different pre- strain level.

4.4 Dislocation density

Table 4.3 shows the dislocation density of BH 220 steel calculated at different conditions. Initially, dislocation density of the as-resaved steel sample was calculated from XRD data as described in experimental process and Fig. 4.19 shows the XRD plot of as-received, 0.001/s , 0.1/s strain rate broken sample.

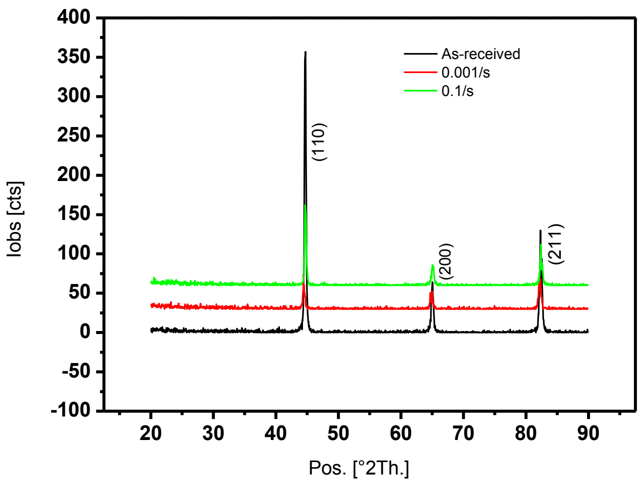


Fig 4.19: XRD diagram of as-received, 0.001/s and 0.1/s strain rate broken sample.

Table 4.3: Dislocation density of BH220 steel at different conditions

Strain rate/condition		**Dislocation density**
As received material		1.0259×10^{10}
Strain rate 0.001/s	0% (no pre-strain or baking)	1.34469×10^{11}
	2% pre+ baking	1.0736×10^{10}
	8% pre+ baking	2.94339×10^{11}
Strain rate 0.1/s	0% (no pre-strain or baking	4.876×10^{11}
	2% pre+ bake	3.0417×10^{11}
	8% pre + bake	1.0422×10^{12}

From table 4.3 it can be observed that as received sample has lowest dislocation density and after tensile testing at different strain rates, all the pre strained samples showed increase in density. But overall increase in dislocation density is only two orders in magnitude and this can be attributed towards the cold rolled nature of the as received steel. With increase in strain rates the sample exhibits higher dislocation density. This can be attributed to the multiplication of dislocation to cope up with the higher deformation rate. Moreover, it can also be observed that at higher pre strain value the density is more in general as expected. But, at 2% pre-strain the value is slightly lower. This may be due to formation of dislocation cell structure as mentioned by earlier researchers [24, 25].

CHAPTER-5: Epilogue

CHAPTER-5: EPILOGUE

5.1 Conclusions

1. The yield strength and ultimate tensile strength values of as received specimen as well as bake hardening specimen increases with increase in strain rates and pre-strain level.
2. The strain hardening exponent of pre-strained condition and bake hardened condition decreases as per the pre-strain level increases.
3. For a particular pre-strain level, higher strain rate shows higher 'n' value compare to slower strain rate.
4. (%) uniform elongation after bake hardening decreases with increase in pre-strain level as well as strain rate.
5. BH response increases as the pre-strain level is increased; whereas, at a particular pre-strain level, lower strain rate yields maximum BH value.
6. As per the study of fracture surface of as-received sample at 0.001/s strain rate mixed mode of fracture has accrued.
7. The dislocation density value is lower in 2% pre-strain bake hardened condition compared to 0% condition and again increases with increase in pre- strain level.

5.2 Future scope of work

1. Study of bake-hardening behaviour of ultra-low carbon BH 220 steel at more higher (200, 400& 500 /s) strain rates.
2. Correlation of the engineering stress- strain behaviour with fractrographs at higher strain rates.
3. Dislocation density study at these higher strain rates.

CHAPTER-6: Reference

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